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Flares from spiral waves by lensing and time-delay amplification?

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ABSTRACT
Episodically accreting black holes are thought to produce flares when a chunk of particles is accelerated to high velocity near the black hole horizon. This also seems to be the case of Sagittarius A* in the Galactic Center, where the broad-band radiation is produced, likely via the synchrotron self-Compton mechanism. It has been proposed that strong-field gravitational lensing magnifies the flares. The effect of lensing is generally weak and requires a fine-tuned geometrical arrangement, which occurs with only a low probability. However, there are several aspects that make Sagittarius A* a promising target to reveal strong gravity effects. Unlike type II (obscured) active galaxies, chances are that a flare is detected at high inclination, which would be favourable for lensing. Time delays can then significantly influence the observed flare duration and the form of light-curve profiles.

Here we discuss an idea that the impact of lensing amplification should be considerably enhanced when the shape of the flaring clump is appropriately elongated in the form of a spiral wave or a narrow filament, rather than a simple (circular) spot which we employed previously within the phenomenological 'orbiting spot model'. By parameterizing the emission region in terms of the spiral shape and contrast, we are able to extend the spot model to more complicated sources. In the case of spirals, we notice a possibility that more photons reach a distant observer at the same moment because of interplay between lensing and light-travel time. The effect is not symmetrical with respect to leading versus trailing spirals, so in principle the source geometry can be constrained. In spite of this, the spot model seems to provide entirely adequate framework to study the currently available data.

Keywords: Black holes – Galactic Center (Sgr A*) – Accretion – Gravitational lensing

1 INTRODUCTION

Temporal changes of the radiation flux are frequently reported in active galactic nuclei (AGN) as well as Galactic black-hole candidates, i.e., two categories of objects that contain accreting black holes (for reviews of AGN variability, see e.g. McHardy & Czerny 1987; Lawrence & Papadakis 1993; Done 2002; Gaskell & Klimek 2003; Vaughan, Fabian & Iwasawa 2005). Especially X-rays vary a lot and on short time-scales. Variability time-scales extend down to the shortest resolvable intervals and seem to scale with the black hole mass (Mirabel & Rodríguez 1998; Papadakis 2004; Done & Gierliński 2005). Persisting fluctuations are occasionally dominated by more substantial increases of the radiation flux. These events have been dubbed 'flares' and often attributed to instabilities/shocks operating in black-hole accretion flows (Haardt, Maraschi & Ghisellini 1994; Poutanen & Fabian 1999; Życki 2002; Czerny et al. 2004; Goosmann et al. 2006). One can expect that fast bulk (orbital) motion and lensing play a role in amplification of the flaring signal.

In the dynamical center of our Galaxy, a peculiar radio source, Sagittarius A* (Sgr A*), is located (e.g. Eckart, Schödel & Straubmeier 2005). It is very compact and presumably contains a supermassive black hole. Given a relatively small distance ($D \simeq 8$ kpc) and a large mass of the black hole ($M_{\bullet} \simeq 3$–$4 \times 10^6 M_{\odot}$), a silhouette of Sgr A* should draw a circle of diameter $\simeq 10.4 r_{\rm g}/D \simeq 42\mu$arcsec on the sky. Furthermore, a gaseous torus is not detected in Sgr A*, and so the central region can be viewed at high inclination, something which is quite impossible in obscured AGN.

In spite of a very low level of its activity, flares of duration $\simeq t_{\rm K}(r_{\rm ms})$ have been reported also from the Galactic Center (Baganoff et al. 2001; Genzel et al. 2003; Marrone et al. 2006; Bélanger et al. 2005, 2006). Duration of short flares is comparable with Keplerian orbital period near the marginally stable orbit, $t_{\rm K}(r_{\rm ms})$, and it is not much longer than the light-crossing time across one gravitational radius: $t_{\rm c} \equiv r_{\rm g}/c$, $r_{\rm g} \equiv GM_{\bullet}/c^2 \approx 1.5 \times 10^{11}\, M_6\,{\rm cm}$, $M_6 \equiv M_{\bullet}/10^6 M_{\odot}$.

The flares occur about once per day from within a few milli-arcseconds of Sgr A* radio position. Because of short time-scales they cannot be explained in terms of viscous processes in the standard accretion disc with some appreciable accretion rate (as already mentioned, there is no evidence for a standard-type axially symmetric accretion regime); Sgr A* is accreting at a highly sub-Eddington rate. Nonetheless, recent millimeter, infrared and X-ray observations have confirmed these irregular outbursts lasting between $\simeq 20$ minutes and about 2 hours. They are probably generated by relativistic acceleration of electrons in the innermost region, where synchrotron radiation emerges followed by inverse Compton mechanism (Markoff et al. 2001; Yuan et al. 2003; Liu, Melia & Petrosian 2006). There are indications for 17–20 min quasi-periodicities to be present in light curves of some of these flares (Genzel et al. 2003; Eckart et al. 2004). The influences of relativistic lensing and Doppler effects have been considered in connection with Sgr A* since more than a decade ago (e.g. Hollywood & Melia 1995; Melia et al. 2001). These effects are now of imminent interest because of growing amount of new data gathered in different wavebands.

The model of a bright spot orbiting near a black hole (Cunningham & Bardeen 1972, 1973; Bao & Stuchlík 1992; Karas et al. 1992) has been fairly successful in explaining the observed Sgr A* modulation (Broderick & Loeb 2005, 2006; Meyer et al. 2006a,b; Noble et al. 2007). It has been argued that the flare lightcurves can be understood as a region of enhanced emission, a.k.a. 'spot', that performs a co-rotational bulk motion near above the innermost stable orbit, $r = r_{\rm ms}$. The observed signal is modulated by relativistic effects. According to this idea, Doppler and gravitational lensing influence the observed radiation flux and this can be computed by ray-tracing methods (Dovčiak et al. 2004a,b).

The original idea and the interpretation of the "spot" origin have to be adapted to the conditions appropriate for Sgr A*. To this aim, the phenomenological model of the source is a way of parametrizing the intensification of the signal. This approach can be extended to more complicated geometry of the emission region, like standing shocks and spiral waves, which is what we discuss here. For example, spiral waves as an agent of light modulation have discussed and compared with the spot model by Varnière & Blackman (2005) in the context of quasi-periodic oscillations from accretion discs. On a more physical level it is still not possible to calculate the intrinsic emissivity from first principles, i.e., without enlarging the number of free parameters beyond and reasonable limit.

2 TIME DELAYS FROM SGR A* VICINITY

2.1 Model setup

It is quite likely that the geometrical shape of the flare emission region is deformed by shearing due to strong tidal fields of the black holes, magnetohydrodynamic instabilities operating in the plasma, as well as by the influence of stars passing nearby. Under such circumstances the emission area can be better described as a transient pattern extending in both radial and azimuthal directions. Relativistic effects from spiral waves and standing shocks have been previously invoked to explain spectral features from black-hole accretions discs (Karas, Martocchia & Šubr 2001; Hartnoll & Blackman 2002; Machida & Matsumoto 2003; Fukumura & Tsuruta 2004). Although the Doppler boosting is visible even at a moderate value of the inclination angle, much stronger enhancement can occur via gravitational lensing, provided that a rather precise geometrical alignment with the caustic position is satisfied (e.g. Rauch & Blandford 1994; Bozza et al. 2005).

It has been proposed that a kind of this instability could play a role in forming Sgr A* flares (Tagger et al. 1990, 2006) and since then the idea of spiral perturbations has been greatly advanced (Falanga et al. 2007). Here we put forward a simple argument (based on Karas et al. 2001) that relativistic effects together with finite light travel time from different elements of the spiral source may add up together and enhance the observed flare signal from Sgr A*. For suitable spiral shapes, $r \equiv r(\phi)$, the enhancement can reach quite significant levels. Lightcurve profiles depend on observer inclination, $\theta_{\rm o}$, and the emission radius as the principal

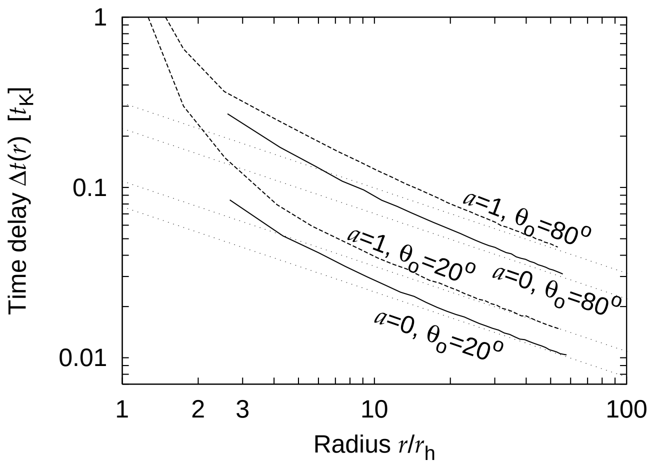

Figure 1. Graphs of the maximum time delay $\Delta t(r)$ for photons originating from an r = const ring rotating in the black-hole equatorial plane. The delay is plotted in units of the Keplerian orbital period, $t_{\rm k} \simeq 31(r^{\frac{3}{2}} + a)M_6$ sec. Radius is expressed in $r_{\rm h} = [1 + \sqrt{1 - a^2}]^{1/2} r_{\rm g}$. Four cases are shown with different spin a of the black hole and inclination $\theta_{\rm o}$ of the observer. The Euclidean estimate is plotted by dotted lines of $-1/2$ slope. Towards low radius the relativistic delay grows more rapidly than the estimate because of fast motion and strong gravity.

parameters, which in turn may depend on the black hole spin a through $r_{\rm ms}(a)$ dependency.

Let us assume that a perturbation of local emissivity structure develops on length-scales of $\simeq$ 10–20$r_{\rm g}$ extending along a logarithmic spiral pattern $r \equiv r(\phi)$ (Karas et al. 2001). The spirals become active either by their intrinsic synchrotron emission and Compton up-scattering or the illumination from a primary source. Although our model is a phenomenological one, such kind of spirals are expected to arise by several mechanisms in accretion discs: spiral waves represent large-scale structures (size comparable with the radius) that can be induced by non-axisymmetric instability mechanisms.[1] Also, a pattern resembling a single-armed spiral is produced from an extended spot after its decay due to shearing (Karas, Vokrouhlický & Polnarev 1992)

[1] Most of the attention towards gaseous spiral waves has been originally motivated by studies of cataclysmic variables. It has been recognized that the variation of the density profile and of the ionization structure of accretion flows, predicted by numerical and semi-analytical methods, is followed by temperature modulation and, therefore, a change in the gas (thermal) emissivity within the spirals. A similar effect is expected for the X-ray irradiated accretion flows in AGN. Sanbuichi, Fukue & Kojima (1994) first considered the spirals extending close to a Schwarzschild black hole and they showed examples of relativistically distorted spectra where the effects of general relativity play a role.

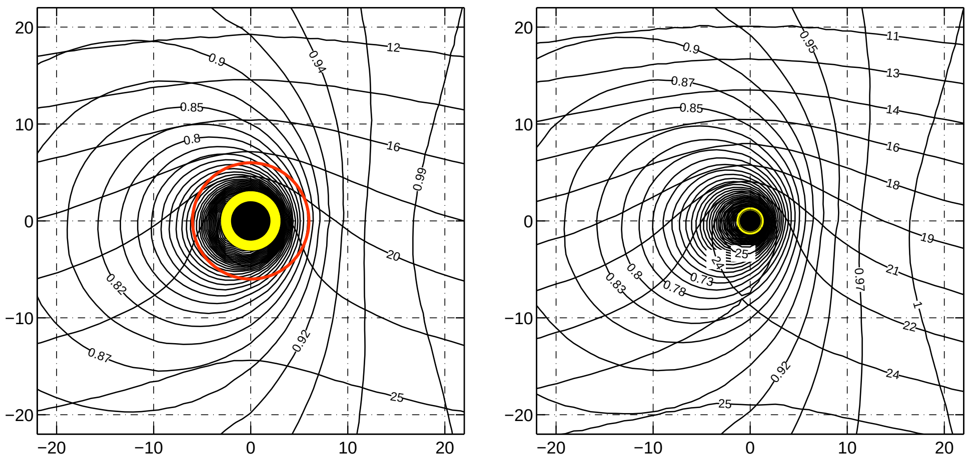

Figure 2. Levels of light-travel time $t(r, \phi) = \text{const}$ (approximately horizontal direction of the contour lines) are plotted together with levels of the redshift function $g(r, \phi) = \text{const}$ (roundish shape of the latter). The contours are constructed in the equatorial plane of Kerr black hole for two cases: a non-rotating hole ($a = 0$, left panel) and for a maximally rotating hole ($a = 1$, right panel). Observer is located towards top of the figure (at the inclination of $\theta_{\rm o} = 20^{\rm o}$). The argument of this paper assumes that the spiral pattern crosses $t = \text{const}$ contours and the signal varies thanks to their deformation and thanks to lensing near the horizon. Geometrical units are used for time t (conversion to physical units as in the previous figure caption); redshift function g is dimensionless and it attains values around unity ($g > 1$ corresponds to the blue-shift, i.e. observed energy of photons higher than the rest-frame energy). Three circles are plotted around the center: the horizon radius ($r = r_{\rm h}$, black), the circular photon orbit ($r = r_{\rm ph}$, yellow), and the marginally stable orbit ($r = r_{\rm ms}$, red). The circles coincide with each other in the extremely rotating case: $r_{{\rm h}|a=1} = r_{\rm g}$.

or it may be produced by debris in the wake of a tidally captured and disrupted satellite (e.g. Gomboc & Čadež 2005).

One should emphasize that the physical conditions leading to the spiral-shaped source of X-rays must be very different from those envisaged by the orbiting spot model, although, on the phenomenological level the two models do not appear to be that much different (they can be treated by similar numerical schemes). The spot model has been built on the standard disc, which is illuminated by coronal flares; otherwise it remains almost intact. Spots are merely the reflection features that come into existence only by flares and they cease as soon as the irradiation is diminished. On the other hand, the existence of extended spirals probably requires that the base flow is non-axisymmetric and, hence, profoundly different from a standard disc – self-gravity, external forcing by another body, or MHD processes must be invoked to create the spirals and calculate their form. They light up themselves by the synchrotron mechanism.

2.2 Time-delay calculations and the signal enhancement

We calculated the light-travel time from the equatorial disc around a Kerr black hole to a distant observer. Apart from the central mass $M_\bullet$, the situation is characterized by parameters a (dimension-less black hole spin) and $\theta_{\rm o}$ (inclination angle).[2] The complexities of primary X-ray reprocessing can be hidden by parameterizing the emissivity in the form of a logarithmic spiral wave. The emission region extent and shape are then defined by the spiral-wave pitch angle and the emissivity contrast – two variables that can be fitted to actual data.

Adopting the phenomenological approach does not merely hide the unknown physics. It also allows us to distinguish the principal difference of the two models, i.e. their geometry, while the "physical" models in reality rely on a number of free input parameters that have to be set.

We first estimate the light-crossing time across the spiral-wave extent. It comes out of the order of $t_{\rm c} \approx 10 M_6$ sec. On the other hand, the orbital, thermal, sound-crossing, and viscous time-scales are typically longer than $t_{\rm c}$. Radiation arrives at the observer from different regions of the source, so that individual light rays experience variable time lags. Time intervals get longer very near to the hole because of gravitational delays predicted by general relativity, including the frame-dragging effect near a rotating black hole, which we also take into account.

The geometrical time lag (along different rays) can be characterized by the maximum value $\Delta t(r)$, which also indicates whether the Euclidean formula gives a correct value of the light-travel time with an acceptable precision. Figure 1 shows Δt for a source located near $r = r_{\rm ms}$. Solid curves represent the delay values in Kerr spacetime, while the dotted lines show the approximation in flat space. Relativistic corrections are increasingly important for $r \lesssim 5 r_{\rm g}$, where $\Delta t(r)$ increases sharply. On the other hand, the difference between the exact value of Δt and its Euclidean approximation is less than 10 % for a source location $\gtrsim 5 r_{\rm g}$ (see Karas et al. 2001).

Figure 2 shows contours of relative time delay between a ray coming from a given radius in the equatorial plane ($\theta = 90^{\rm o}$), and an (arbitrarily chosen) reference ray. In this figure, time delay was calculated in Kerr metric. Clearly, the contours are progressively deformed and even split as the emission radius approaches the black-hole horizon. Reference values quoted with the contours of this figure can be transformed to physical time units (measured by a distant observer) by the relation $\bar{t}\,[\mathrm{sec}] \approx 10 M_6\, t$. Furthermore, contours of constant redshift $g(r, \phi) = \mathrm{const}$ are over-plotted in Fig. 2. Radiation flux is enhanced (or diminished) by factor g^4 as it originates from the regions approaching (receding) the observer.

Fig. 2 once again suggests the main grounds for the enhancement of the observed signal. The enhancement occurs when photons emitted at different points of the

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[2] We employ standard notation for the Kerr spacetime in Boyer-Lindquist coordinates and geometrized units ($c = G = 1$; e.g. Misner, Thorne & Wheeler 1973). All lengths and times are made dimensionless by expressing them in units of the typical mass of the central black hole. Radius is supposed to be greater than the marginally stable orbit, i.e. $r_{\rm ms} = 3 r_{\rm g}$ for a non-rotating black hole ($a = 0$), and $r_{\rm ms} = 1 r_{\rm g}$ for a maximally rotating black hole ($a = 1$).

rotating source reach the observer similar time. This is possible near the black hole ($r \lesssim 6r_{\rm g}$), where $t(r,\phi) = $ const contours are bent significantly. The actual shape of the spiral supporting the signal enhancement depends also on the pattern rotation, i.e., not solely on the spacetime geometry. Needless to say, the effect combines with the lensing and Doppler amplification as the source crosses the lensing caustics in $g > 1$ region.

Obviously the effect grows with spin of the black hole and attains maximum at $a = 1$, a theoretical upper limit for Kerr black hole. The difference from the canonical $a = 0.998$ case is rather minimal, except for a small shift of $r_{\rm ms}(a)$ radius. That shift can prove to be important for the disc emission though, provided that the inner edge of the disc is attached to $r = r_{\rm ms}$.

3 DISCUSSION

As mentioned above, the interplay of lensing and the Doppler boosting was discussed by many authors within the orbiting spot model, whereas the influence of time-delays has not been emphasized to such detail. The effect is noticeable when watching the well-known animations of an orbiting spot at a large view-angle inclination (e.g. Fig. 3 in Eckart et al. 2007): the signal is sharply enhanced at the moment when the large spot moves behind the black hole. In the case of a spiral-shaped emission region the effect is expected to be even more pronounced thanks to the elongated size of the source.

The amplification is not symmetrical between leading and trailing spirals of otherwise the same geometry and the intrinsic emissivity. Put in a different way, the timing properties of the flare lightcurves can in principle constrain the ratio of v_r/v_ϕ of the spiral pattern producing them. In particular, for $v_r = 0$, $v_\phi = v_{\rm K}$ the model is effectively reduced to the orbiting spot model, whereas for $l = $ const (constant angular momentum of the gas), $v_r < 0$, $v_\phi < v_{\rm K}$ the case goes over to the falling spot model. Very exciting is now the possibility of having an extended source which can be incorporated within the spiral model. On the other hand the effects of lensing and the delay amplification should not be so important in the case of a low-angular momentum inflow ($v_\phi \ll v_{\rm K}0$), which has been also widely applied in the context of Sgr A* (Proga & Begelman 2003; Moscibrodska et al. 2007, and references cited therein).

Further, it has been recognized that relativistic effects can strongly influence the observed signal and enable us to measure physical parameters of Sgr A* black hole. The simultaneous near-infrared and X-ray flares as well as the steady microwave emission from Sgr A* may be important probes of the gas dynamics and space-time metric of the black hole. The enhancement of the signal discussed in the present paper should be seen in all wavelengths as long as the approximation of geometrical optics is satisfied.

We have argued that the emitting region is likely to be twisted into a shape more complex than a simple spot. The spiral pattern is a physically sound possibility for the flaring region, in which the effect of relativistic modulation is more pro-

nounced. The enhancement of the main peak of the lightcurve takes place roughly on time-scale of the spiral pattern crossing the equal-time curves. In other words the duration of the event can be significantly shorter that the pattern rotation period (it depends on the spiral shape and its rotation law). On the other hand, the pattern orbital speed is still relevant for the estimation of the flare periodicity over the entire cycle.

Given a specific mechanism to generate the spiral waves, certain freedom remains in the model parameters, so the actual form of the spiral profile can vary. Because for an ideal geometrical alignment of the spiral a rather sharp enhancement of the observed signal is foreseen (i.e., stronger than the spot model would predict), we can expect occasional strong flares with amplitudes exceeding the more frequent and currently known flares from Sgr A*.

4 CONCLUSIONS

Albeit physically substantiated, the model of an extended emission region suffers from a practical disadvantage in comparison with the spot model. The spiral model is more complex and the number of parameters describing the source is greater. Therefore, the fitting procedure will need better quality of future data. The spiral model assumes mechanisms beyond the standard disc scheme play a major role and form these non-axisymmetric structures. This may or may not be true. After all, the two scenarios – spots versus spirals – can be relevant for different categories of objects and different regimes of accretion. To this uncertainty refers the question mark in the title of the paper. The advent of simultaneous X-ray and IR detections of Sgr A* flares and the improving temporal and polarimetric resolution offer a promising potential to remove ambiguities that still hamper the association between physical models and real data.

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